

Acoustic and Electromagnetic Reverberation Chambers: Similarities and Differences

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Abstract—Acoustic reverberation chambers predate electromagnetic (EM) reverberation chambers. EM reverberation chamber researchers occasionally make reference to acoustic equivalents when describing test methods and results. However, most EM reverberation chamber users are not familiar with acoustics and may not be aware of similarities and differences. This paper presents a sampling of results for acoustic and EM reverberation chambers, how they relate, and explore whether insights from acoustics can help inform EM reverberation chamber use.

Keywords—acoustics; reverberation chambers

I. INTRODUCTION

Acoustic reverberation chambers were in use well before electromagnetic reverberation chambers were first proposed in the late 1960s [1] and early electromagnetic reverberation chamber researchers make reference to acoustic and thermodynamic equivalents when describing their work [e.g., 2]. However, many current EM reverberation chamber users may not be familiar with reverberation acoustics, and thus not aware of similarities and differences. This paper presents a brief sampling of results for acoustic and electromagnetic reverberation chambers, how they relate, and explores whether results from acoustics can help inform reverberation chamber use.

II. BACKGROUND

A basic understanding of sound as a propagating wave dates back to the Romans (200 BC), if not earlier, and empirical application to room acoustics goes back centuries in the design of concert halls, churches, and other large acoustic spaces. However, room acoustics as a science really began in 1895 with the work of Wallace Sabine, a young Harvard University physics professor [3]. At the time, Harvard had recently completed construction of the new Fogg Lecture Hall which was to be a centerpiece facility; however, the reverberation in the room was so long that a person speaking could not be well understood as word sounds lingered and mixed with the next spoken word, much like interference due to multipath. Correcting the acoustics was considered impossible by senior staff in the physics department and so the assignment was passed down to Sabine, although he had no particular background in acoustics. Sabine used an organ pipe (512 Hz), a stop watch, and his ear to establish that reverberation time (T_{60} , from full sound to not audible, roughly 60 dB in his case) for rooms large compared to the wavelength (overmoded) was

directly proportional to the volume (V) and inversely proportional to the absorptive surface area (A):

$$T_{60} = \frac{0.161V}{A} \quad (1)$$

The Fogg Lecture Hall when empty had a T_{60} of about 5.5 s whereas other good lecture halls Sabine measured had values just below 1 s (about 0.8 s is considered optimal). Sabine introduced absorbing materials (seat cushions, drapes, carpet) to reduce the reverberation time to an acceptable level, in essence modifying the chamber quality factor (Q) similar to introducing absorber in an electromagnetic reverberation chamber to accelerate reverberant decay. While (1) holds only in an averaged sense and is restrictive, it established an important starting point that later researchers built upon to formulate modern room acoustics.

III. BASIC EQUATIONS

The basic wave equations for the acoustic (AC) and electromagnetic (EM) cases in a homogenous space are familiar. We write them here as:

$$\begin{aligned} (\nabla^2 + k^2)p &= 0, \quad p = P_0 e^{-ikz}, \quad \text{AC} \\ (\nabla^2 + k^2)\vec{E} &= 0, \quad \vec{E} = \vec{E}_0 e^{-ikz}, \quad \text{EM} \end{aligned} \quad (2)$$

where p represents wave pressure, \vec{E} the electric field (a similar expression exists for the magnetic field), an $i\omega t$ time convention is assumed, $\omega = 2\pi f$, f is the frequency, $k = \omega/c$, z denotes position, and c is the AC or EM wave propagation speed in the medium, here assumed to be homogenous. The solutions of (2) represent plane waves with magnitudes P_0 and E_0 respectively, with the primary difference being that \vec{E}_0 is transverse (two polarizations, in the plane of propagation and perpendicular), while P_0 is longitudinal.

The field in an AC or EM reverberation chamber can be well modeled as a superposition of plane waves with arbitrary direction and magnitudes, see [3, 6.1] for the AC case and [4, 7.1] for the EM case. A field that is direction- and position-independent in its averages is termed diffuse and is an ideal that both types of reverberation chambers seek to produce over a large test volume. Both AC and EM reverberation chambers can use moving diffusers, such as rotating paddles and curtains, as well as fixed diffusers, such as suspended spheres and periodic structures [5], to improve performance.

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IV. ABSORPTION AND REVERBERATION

The absorptive area A in (1) can be generalized to account for different materials, apertures, and levels of absorption:

$$A = \sum_i \alpha_i S_i \quad , \quad (3)$$

where α_i is the absorption coefficient associated with the surface element S_i , and $\alpha = 1 - r^2$ for any given surface element, where r is the reflection coefficient (amplitude of the reflected wave over amplitude of the incident wave). Thus, α can be related to aperture loss and wall losses in an EM reverberation chamber. An open window (no reflection) has a value of $\alpha = 1$. Values for α at 1 kHz range from 0.04 for brick, to 0.12 for glass, 0.37 for heavy carpet on concrete, 0.69 for 5 cm-tall grass, and 0.99 for 2 cm-thick suspended acoustical tile.

In acoustics, absorptive area is given the units sabins (m^2) and is related to EM absorbing cross section. Values have been measured carefully for persons and seats, as these are two of the primary absorbers in concert halls and lecture rooms, where acoustic design is critical. A seated musician with instrument is about 1.08 sabins at 1 kHz, a cloth covered seat about 0.67 sabins at 1 kHz, and a man standing with a heavy coat about 1.30 sabins at 1 kHz. While ideally the absorptive area is intrinsic to the object in a diffuse field, in a practical chamber location issues, such as when two objects are positioned close to each other or an object is on the floor versus suspended into the diffuse volume, are important variables. This is similar to the case of RF absorber suspended or near a floor, wall, etc. in an EM reverberation chamber [6].

A more general form of (1) for the decay function in an AC reverberation chamber [3, eq. 6-1.4] along with the EM equivalent [4, eq. 1.51] are given by:

$$\begin{aligned} W_{AC} &= e^{-\left(\frac{Ac}{4V}\right)t} \quad , \\ W_{EM} &= e^{-\left(\frac{\omega}{Q_{EM}}\right)t} \quad , \end{aligned} \quad (4)$$

where c is the speed of sound in the AC chamber medium, ω is the angular frequency, and Q_{EM} is the quality factor in the EM case. In the EM case, if we assume a plane wave normally incident on a highly conducting wall, then it is straight forward to find the reflection coefficient and the equivalent absorption coefficient which is $\alpha_{EM} = 4\pi \frac{\delta}{\lambda}$. Using (4), we can equate exponents and then substitute in this equivalent absorptive coefficient yielding

$$Q_{AC} = \omega \frac{4V}{Ac} = 8\pi \frac{V}{\lambda \alpha S} = \frac{2V}{\delta S} = Q_{EM} \quad , \quad (5)$$

where Q_{EM} is the same as [4, eq. 1.43] for the EM case. Q_{EM} is a rough approximation which doesn't fully account for the polarization (direction) of the EM field near the boundary, but is actually quite close to the better estimate found, once direction is considered [4., eq. 1.44].

Spatial autocorrelation functions look very similar for both chamber types. For the acoustic pressure [3,6-8.2] and total electric field [4,7.47], we have:

$$\begin{aligned} \langle p(x, t), p(x + \Delta x) \rangle &= \langle \bar{p}^2 \rangle \frac{\sin(k|\Delta x|)}{k|\Delta x|} \quad , \\ \langle \bar{E}(0) \cdot \bar{E}(\hat{z}r) \rangle &= E_0^2 \frac{\sin(kr)}{kr} \quad , \end{aligned} \quad (6)$$

where x and z represent spatial offsets.

Averaging to achieve a good diffuse field can take multiple forms, as indicated above, including modal stirring, frequency stirring, and position stirring. In acoustics an equivalence between frequency stirring and position stirring for acoustic pressure is given by [3, 6-8.14]

$$k\Delta L \approx \tau\Delta\omega \quad , \quad (7)$$

where $\Delta\omega$ is the bandwidth change, τ is the decay constant defined by (4), and ΔL is the position change. Substituting for τ using (4) yields

$$\frac{A\Delta L}{4V} = \frac{\Delta\omega}{\omega} \quad . \quad (8)$$

This result suggests that averaging over a larger bandwidth (including more modes) is equivalent to averaging over positions roughly in proportion to the wall loss to volume ratio. This is consistent with measured results for a NIST chamber [4, Figs. 9.2 – 9.3].

Differences arise from the differences between the AC scalar wave equation [3, eq. 6-61] and the EM vector wave equation [3, eq. 1.31]. An example is mode numbers and density:

$$\begin{aligned} N_{AC}(\omega) &\approx \frac{1}{6} \frac{V}{\pi^2} \frac{\omega^3}{c^3} \quad , \quad \frac{dN_{AC}}{d\omega} = \frac{1}{2} \frac{V}{\pi^2} \frac{\omega^2}{c^3} \quad , \\ N_{EM}(\omega) &\approx \frac{1}{3} \frac{V}{\pi^2} \frac{\omega^3}{c^3} \quad , \quad \frac{dN_{EM}}{d\omega} = \frac{V}{\pi^2} \frac{\omega^2}{c^3} \quad . \end{aligned} \quad (9)$$

Note the difference by a factor of 2, representing the lack of vector polarization (TE, TM) in the acoustic case. Other differences exist due to the presence of a propagating medium and wave pressure. The full paper will explore the above similarities and differences in more detail.

An interesting acoustics insight with potential for application in coexistence testing is the ‘‘cocktail party effect’’. This is the situation where multiple persons are speaking in a reverberant room which raises the sound level causing persons to cluster in groups. These clusters tend to be separated by a distance large enough so that each cluster is dominated by the direct path sound and the other clusters contribute not directly but through reverberant sound. This is a similar situation to the unstirred versus stirred energy case discussed in [4, Section 9.2] For a person to understand the conversation in a cluster, the signal to noise ratio (direct conversation to other diffuse talkers) has to be greater than 1. Given K clusters (groups of people or source locations) and assuming isotropic sound radiation from each person (spherical spreading), we can show that

$$\frac{S}{N} = \frac{\left(\frac{r_0}{r}\right)^2 + 1}{K-1}, \quad (10)$$

where r_0 is the radius of reverberation similar to r_e as defined in [4, eq. 9.23] for the EM case where the direct (unstirred) energy becomes equal to the indirect (stirred) reverberant energy. Expression (10) could be used as a starting point to describe a coexistence test in a reverberation chamber where K devices with similar radiated powers are causing potential interference. Adding sources (increasing K) reduces the S/N but also will increase loss; however, the increased loss will be dominated by increased noise power for reasonable values of K . As we increase the use of unlicensed spectrum with multiple emitters confined to reverberant volume, an EM version of the “cocktail party effect” may help guide how devices can be tested in advance for their ability to understand a conversation; that is, to maintain a reliable wireless link.

V. CONCLUSION

This paper has touched on some of the similarities and differences between acoustic and electromagnetic reverberation chambers. Acoustics reverberation chamber research has long focused on loss mechanisms and multiple sources. The insights gained may prove useful to the EM reverberation chamber community as we continue to look at questions related to multipath, communications systems, coexistence testing, and other problems different from an unloaded, very high Q chamber.

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